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Induced Magnetic Anisotropy in Thin Ferromagnetic Films Investigated at Low Temperatures

A. A. HIRSCH and N. FRIEDMAN

Department of Physics

Technion - Israel Institute of Technology, Haifa, Israel

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Induced Magnetic Anisotropy in Thin Ferromagnetic Films Investigated at Low Temperatures

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Department of Physics

Technion - Israel Institute of Technology, Haifa, Israel

Abstract

A new mothod of investigation of induced magnetic anisotropy in thin films is given, which is based on the study of the magnetoresistance effect when two crossed magnetic fields are applied. The experiments were carried out from liquid air down to liquid helium temperatures on thin evaporated films of pure nickel or pure iron placed in a rotated cryostat. It was shown that when the films are deposited in an external magnetic field in a vacuum of 10^{-6} mm of Hg, the easy axis of magnetization is induced in the direction of the external field. Because of the dependence of the electric resistivity on the orientation of domain magnetization, the magnetoresistance effect can be a useful tool in the investigation of the magnetization process and the anisotropies of films. The experimental data were compared with a theoretical model suggested for the magnetization of films under the influence of two crossed magnetic fields. This model was elaborated by means of the approximation of coherent rotation of electron spins in a single domain particle, whose anisotropy was made up of a unidirectional, a uniaxial and a cubic magnetocrystalline component. It was found that films deposited in an external magnetic field show a symmetry around the easy magnetization axis like a spheroidal particle around a polar axis. At very low temperatures the induced magnetic anisotropy is more distinct because of vanishing thermal stresses. A process of formation of elongated grains or of chains of small particles seems to be responsible for the induced easy magnetization axis.

Introduction

The origin of induced magnetic anisotropy in thin films of ferromagnetic metals is not yet clear. It has been reported [1] that in iron and nickel-iron films a very small part of this anisotropy might be caused by surface stresses. According to other authors [2] an isotropic strain in Permalloy films creates a magnetoelastic easy axis normal to the film. Magnetic investigations on thin films at very low temperatures seem to be important because of vanishing stresses due to differential thermal expansion between metal and substrate. It is assumed that films made by deposition in a vacuum of 10^{-6} mm of Hg, as studied in this work, have a granular structure. Such films have normally a negative temperature coefficient of electric resistivity. Because of this granular structure a simple single domain model for the hysteresis phenomena in the films is suggested.

Asymmetrical Hysteresis in a Uniaxial Domain

The result of applying two perpendicular crossed magnetic fields on a uniaxial single domain, one variable H and another constant H', which are inclined at the angles ϕ and $90^{\circ} - \phi$ to the easy axis, is the formation of asymmetrical hysteresis magnetization curves. One calculates these curves in the usual way assuming coherent rotation of spins. The only important energy terms taken into consideration are conditioned by magnetic anisotropies (unidirectional which stems from the constant field H', magnetocrystalline and uniaxial) and by interaction between H and the spontaneous magnetization M_s. When H and H' are in the [100] and [010] directions, $\phi = 45^{\circ}$, and the cubic magnetocrystalline anisotropy constant K is negative, one represents the magnetization hysteresis curve in reduced units by the relation

$$h = (2\,m^2 - 1)\left[m + \tfrac{1}{2}F\,(1 - m^2)^{-\frac{1}{2}}\right] + h'm\,(1 - m^2)^{-\frac{1}{2}} \qquad (1)$$

where $m = M / M_s$; $h = H\,M_s / 2|K|$; $h' = H'M_s / 2|K|$ and $F = K_u / |K|$ is the ratio of unidirectional to magnetocrystalline anisotropy constants. At large values of h' the asymmetrical loops [Eq. (1)] become asymmetrical reversible curves. The hysteresis of the magnetoresistance effect (MRE) shows also similar changes, as illustrated in Fig. 1. One expresses the relative change of resistivity by $\Delta R/R = a\,(m_r^2 - m^2)$ where the factor a is negative for a longitudinal MRE and positive for a transverse MRE ; m_r is the reduced remanence. H becomes normal to the easy axis if the domain is rotated at 90° around the [010] axis from its previous position [Eq. (1)] and one gets a symmetrical loop described by

$$h = (1.5\,m^2 - 0.5)m + h'm\,\sqrt{2}\,(1 - m^2)^{-\frac{1}{2}} + Fm \qquad (2)$$

whose slope dm/ dh and coercive force decrease with increasing h'. The MRE is exhibited in this case by non-saturated symmetrical curves.

<u>Experimental results and interpretation</u>

The transverse MRE studied in thin films varies with the angle Θ between H and the direction normal to the substrate. One gets a transverse-perpendicular MRE ($\perp / \perp$) for $\Theta = 0^\circ$ and a transverse-parallel MRE ($\perp / \parallel$) for $\Theta = 90^\circ$. Several values of Θ are obtained by means of rotation of the cryostat containing the samples. The dc and ac resistance measurements were carried out on films of pure iron or nickel deposited on to cover glass substrates (1 cm x 0.3 cm). The cathode ray oscillograph traces are represented in Fig. 2 - 4 with H' or Θ as parameters. The formation of typical asymmetrical loops is demonstrated in Fig. 2 (a) and Fig. 2 (b). Using the theoretical model, one concludes that the grains of these films have easy axes inclined to the substrate. The film

whose MRE is shown in Fig. 2 (c) was deposited in a field of 75 oe normal to the substrate. The large coercive force and the slight asymmetry in the shape of the loops at large values of H' indicate that an easy axis of magnetization has been induced in a direction nearly normal to the film. In the case of symmetrical loops with small coercive force [Fig. 3 (c)], these easy axes are probably parallel to the plane of the substrate. Both transverse effects illustrated in Fig. 3 (b) and Fig. 3 (c) can be explained by Eq. (1) and Eq. (2) respectively, if the plane (100) is parallel to the substrate and the projections of the magnetization vectors on (100) are parallel to the direction of the electric current. The films whose MRE traces are given in Fig. 4 were deposited in a longitudinal field. The vanishing remanence in the MRE curves and their symmetry at large values of H' would be possible if an easy axis were induced in the direction of the field applied during the deposition of the films. It can be seen from Fig. 4 (c) that the MRE shows a cylindrical symmetry with respect to the induced easy axis as in the case of a wire. The maximal values of $\Delta R/R$ in films with a large uniaxial anisotropy, as found in this work, vary from 1.1% to 1.5%. These values are similar to those reported in a previous work [3] on MRE measurements on thin nickel wires. The similarity between the MRE of these films and thin wires suggests that the induced anisotropy may be related to a process of formation of elongated grains or to an aggregation of small particles in chains.

Concluding Remarks

Vrambout and De Greve[4] have shown by use of the magneto-optic Kerr effect, that in iron films a weak anisotropy axis exists which lies close to the long axis of the substrate. It has been shown by Van Itterbeek[5] that the temperature variation of the coercive force in nickel films may be dissimilar for two different directions (transverse - perpendicular and transverse - parallel) when a single variable magnetic field has been applied. This behaviour was interpreted in an early work[6], assuming an easy magnetization axis which is parallel to the plane of the substrate.

The technique of using two crossed magnetic fields described here has the advantage of enabling one to determine more exactly how the easy magnetization axis inclines towards the substrate. The direction of this axis must be given in general by two angles (an azimuthal and a polar one).

Acknowledgments

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References

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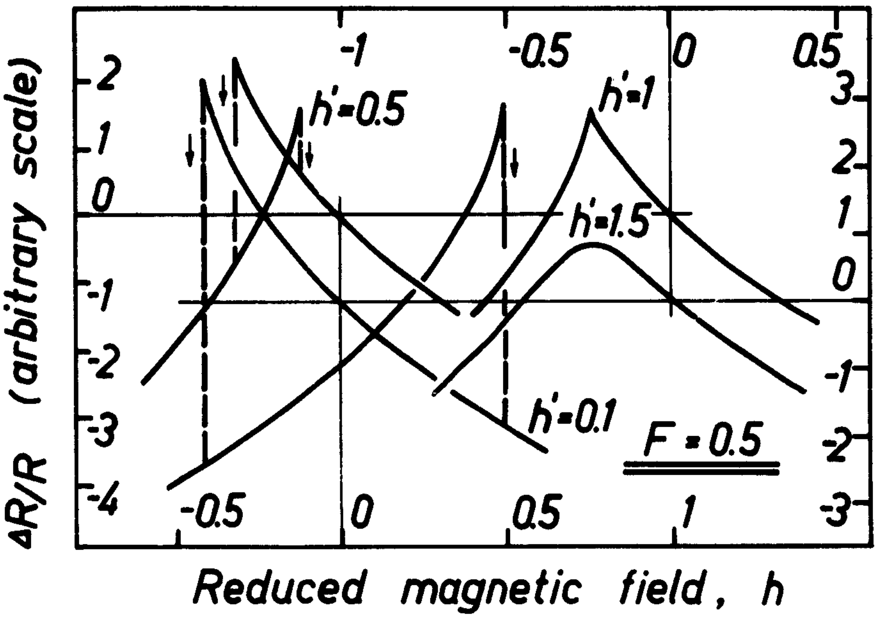
<u>List of figure captions</u>

Fig. 1. Calculated transverse magnetoresistance curves in reduced units. The uniaxial domain has a negative magnetocrystalline anisotropy constant. The field h is along the [100] axis. The constant field h' lies along the [010] axis. The easy magnetization axis is parallel to [110]. The ratio of unidirectional and magnetocrystalline anisotropy constants F is 0.5.

Fig. 2. Static transverse magnetoresistance curves of thin films. Maximum H = 2200 oe. (a) R = 70589 ohm, maximum $\Delta R/R$ = 0.8 %; (b) R = 3472 ohm, maximum $\Delta R/R$ = 0.12 %; (c) film deposited in a field of 75 oe normal to the substrate. R = 19290 ohm, maximum $\Delta R/R$ = 0.07 %.

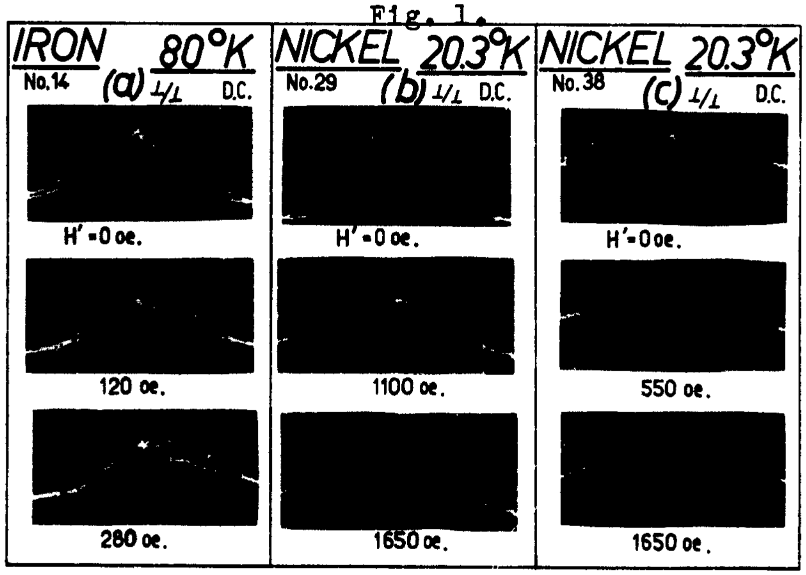
Fig. 3. Static transverse magnetoresistance curves of thin films. Maximum H = 2200 oe. (a) R = 1828 ohm, $\Delta R/R$ = 0.33 %; (b) R = 1303 ohm, maximum $\Delta R/R$ = 0.11 %; (c) R = 11959 ohm, maximum $\Delta R/R$ = 1.25%. Frequency of current in films is 2400 cps.

Fig. 4. Static transverse magnetoresistance curves in thin films. Maximum H = 2200 oe. (a) films deposited in a longitudinal field of 450 oe. R = 20000 ohm, maximum $\Delta R/R$ = 1.5 %; (b) and (c) film deposited in a longitudinal field of 150 oe. R = 18190 ohm, maximum $\Delta R/R$ = 1.1 %.



-1
-0.5
0
0.5
2
1
0
-1
-2
-3
-4
3
2
1
0
-1
-2
-3
h'=0.5
h'=1
h'=1.5
h'=0.1
F = 0.5
-0.5
0
0.5
1
ΔR/R (arbitrary scale)
Reduced magnetic field, h

Fig. 1.



IRON 80°K
No.14 (a)
D.C.
H' = 0 oe.
120 oe.
280 oe.
NICKEL 20.3°K
No.29 (b)
D.C.
H' = 0 oe.
1100 oe.
1650 oe.
NICKEL 20.3°K
No.38 (c)
D.C.
H' = 0 oe.
550 oe.
1650 oe.

Fig. 2.

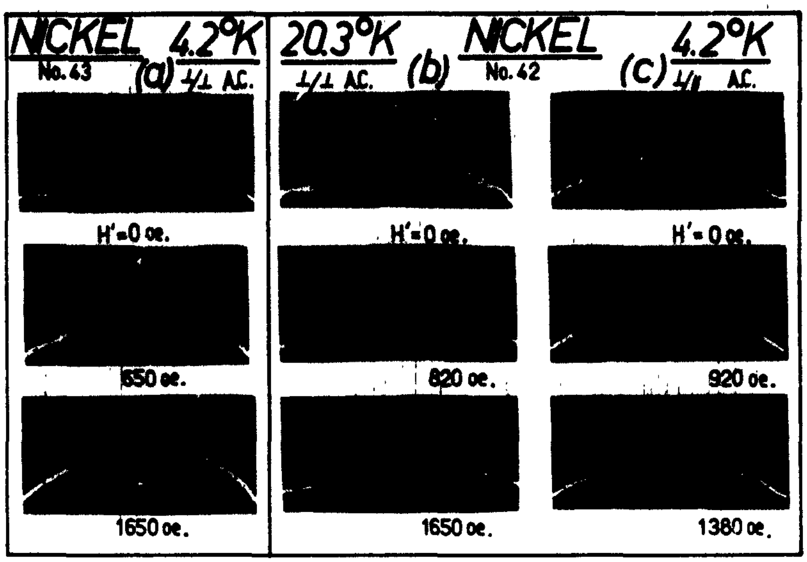

NICKEL
No. 43
4.2°K
(a)
A.C.
H'=0 oe.
650 oe.
1650 oe.
20.3°K
A.C.
(b)
NICKEL
No. 42
H'=0 oe.
820 oe.
1650 oe.
(c)
4.2°K
A.C.
H'=0 oe.
920 oe.
1380 oe.

Fig. 3.

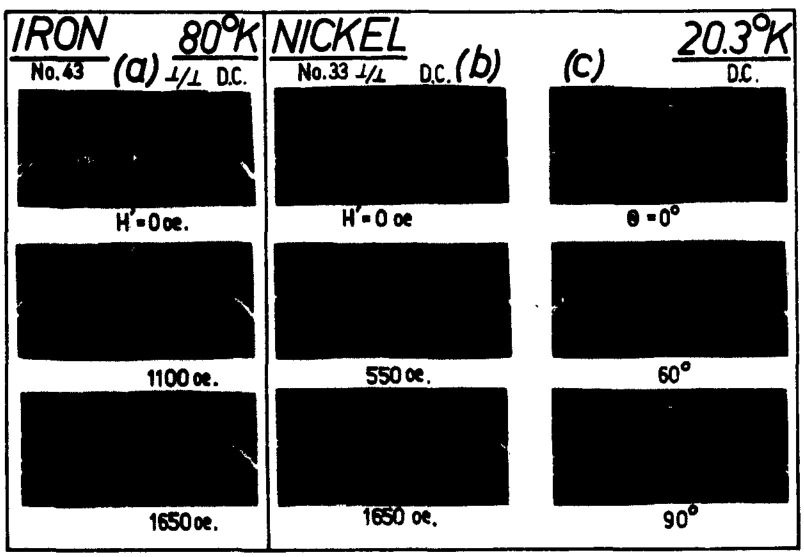

IRON
No. 43
(a)
80°K
D.C.
H'=0 oe.
1100 oe.
1650 oe.
NICKEL
No. 33
D.C.
(b)
H'=0 oe
550 oe.
1650 oe.
(c)
20.3°K
D.C.
θ=0°
60°
90°

Fig. 4.